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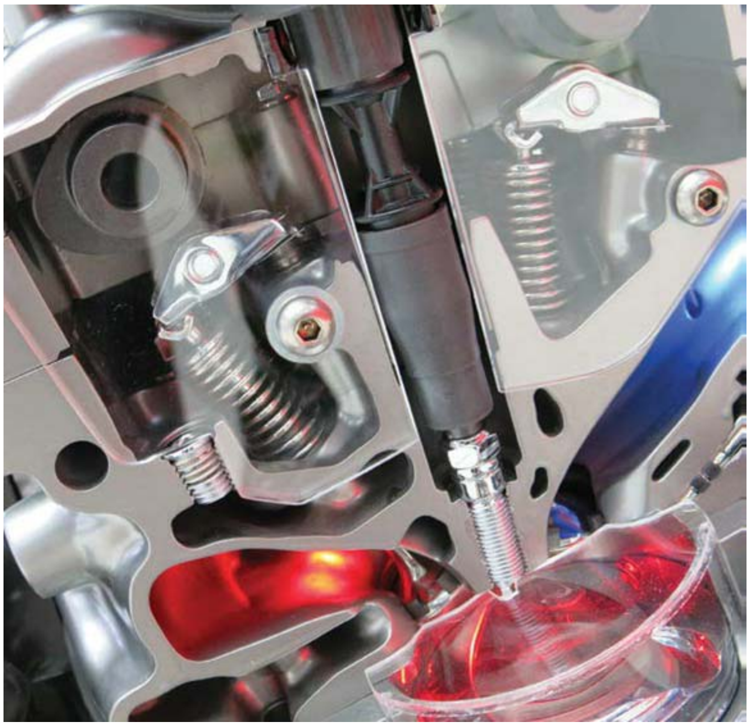
Future ICEs: What comes after 2025?

With 2017-2020 products in the pipeline, what are the over-the-horizon solutions for greater light-vehicle engine efficiency?

by Lindsay Brooke



More capable and flexible cylinder deactivation is under investigation and development by more OEMs. Shown is GM's new-for-2016 3.0-L twin-turbo V6, which employs GM's first production Active Fuel Management for OHC cylinder heads. GM continues testing of Tula Technologies' advanced AFM based on crankshaft angle. Ford is even evaluating a cylinder deactivation system co-developed with Schaeffler Group on the Ford 1.0-L triple. (Lindsay Brooke)

Vehicle engineers and planners have been breathing a bit easier lately, generally confident that the industry will meet the upcoming U.S. CAFE and Euro 6 vehicle CO_2 regulations without excessive disruption and cost to the end customer. But those working in powertrain recognize the period beyond 2025 is uncharted territory.

For the U.S., there's the so-called "mid-term review" coming in early 2018, in which the **EPA** and **NHTSA** government agencies will reevaluate the basis for the stringent 54.5-mpg (23.1 km/L; 4.3 L/100 km) standard. Will they stay the course or make corrections? An informal poll of engineers and scientists conducted at the 2015 **SAE** World Congress by *Automotive Engineering* showed the majority expect rulemakers will not back down from the current regs.

Discussions during Congress week, and at the Vienna Motor Symposium that followed, revealed a new generation of sophisticated combustion strategies currently under development. Many of these, including GCI (gasoline compression ignition), RCCI (dual-fuel reactivity controlled compression ignition), CAI (controlled auto ignition), and others employ moderate-to-high stratified operation. Such strategies require major leaps in in-cylinder control, valve control, plus new fuels and energy sources. All will be needed, along with techniques such as waste-heat recovery, to continue the combustion engine's dominant role.

FCA's Chris Cowland is one of the industry's most vocal advocates for global fuel standardization and higher RON grades. (Lindsay Brooke)

Standing in the way of higher compression ratios and cylinder pressures are the old nemesis "knock" and its evil cousin "super knock"—the latter an increasingly common challenge for boosted engines. Controls, and sensor fidelity and response, will be ever more vital in this battle, causing the electronics portion of total powertrain cost to increase by 15% by 2025, according to the Powertrain Strategies for the 21st Century study published last year by the **University of Michigan's Transportation Research Institute** (UMTRI).

"ICEs have made tremendous efficiency improvements over the past several decades," noted Tom Grissom, Director of Business Development at **BorgWarner Turbo Systems**. "Current benchmark performance in thermal efficiency are above the 30% range for gasoline engines and 40% range for diesel. Estimated near-term improvements are in the 5% range—but further downsizing and downspeeding alone will not result in significantly higher efficiencies," he said.

Added Bob Bienenfeld, American **Honda**'s Assistant Vice President of Environment and Energy Strategy: "There may be more exotic ICE technologies, but much depends upon the pace of the standards after 2025," he said. "If they are aggressive, it is looking like aggressive HEV implementation will be required, if not plug-in

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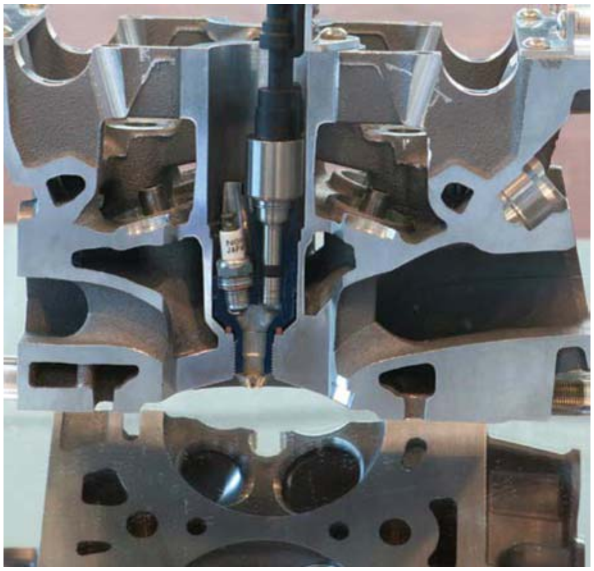

Mahle's patented Turbulent Jet Ignition is among many novel designs aimed at optimizing lean combustion. It's a pre-chamber system that effectively decouples the main and pre-chamber air/fuel charges. The pre-chamber gets 3% of the injected fuel. The system as tested to date has shown improved thermal efficiency and reduced heat losses, but higher NOx levels. (Lindsay Brooke)

Mahle Research Technical Specialist Mike Bunce says work on the Turbulent Jet Ignition system has shown a peak net thermal efficiency greater than 45%, with reduced knock and about a 20% reduction in BSFC in multicylinder testing. Delphi and Ford provide project support. (Lindsay Brooke)

hybrids, battery electrics, and fuel-cell vehicles."

Those technologies may be more cost/benefit effective, he said, "especially if the question is whether or not we develop a new generation of engine technologies, like HCCI (homogeneous-charge compression ignition), or simply go for the next step in terms of transformation. But much will depend on standards, infrastructure, consumer acceptance, the reduction in costs, and, of course, the overall support of GHG regulations."

Bienenfeld noted that Honda is confident PHEVs can deliver as much value as BEVs in such an environment, thus keeping the ICE relevant. But to do this, the industry's challenge "will be translating the many fundamental advances into production-viable hardware," observed Dr. Robert Wagner, Director of Fuels, Engines, and Emissions Research at the **Oak Ridge National Laboratory** (ORNL).

Pushing into lean-burn territory

The latest production engine programs use evolutionary combustion systems that are a preview of early 2020's engines that will combine lean-burn and stoichiometric operation. "I think the high 40% range is feasible for light-duty engine efficiency, without waste heat recovery,"

No debate: Higher octane's great

The industry's march to Otto-cycle compression ratios as high as 15:1—race-engine levels not long ago—has been enabled by combustion control and knock-detection technologies that, in most cases, were designed for relatively low-octane pump fuel. And to further unbridle those engines' full efficiency, powertrain engineers have long been arguing for higher-octane fuel blends.

Their voices rang louder during 2015 **SAE** World Congress week, at both the High-Efficiency ICE Symposium and during panel discussions on fuel octane number and future powertrains.

FEV Inc.'s Vice President of Light-Duty Engines, Dean Tomazic, opened his panel with a recent photo of a gasoline pump in his native Germany. The image showed the 102-RON (research octane number) fuel that's widely available. Such "super premium" fuel helps deliver a 10% increase in fuel efficiency for engines running comp ratios above 11.5:1, he said, compared with a 9.3:1 engine running the 95-RON that's marketed as the mid-grade gas in Europe.

Where in the U.S. 87-93 RON represents the mainstream grades, government-industry alignment in Europe has elevated gasoline octane overall to take advantage of recent engine technologies, Tomazic noted. Experts on the FEV Theater panel said the move to higher octane levels—and the "co-optimization" of fuels and combustion strategies—can reduce CO_2 emissions by 2-5% while improving real-world vehicle fuel economy by up to 6%, with the added benefit of greater torque and power.

Some experts in the petroleum industry have a different perspective. Research engineer Amir Maria of **Chevron Energy Technology** asserted that since North American market engines are calibrated for 87 RON, offering 95 RON (as the new U.S. premium) would have minimal effect on the current vehicle fleet's fuel efficiency, while costing consumers about $1500 in 200,000 mi (322,000 km) of vehicle ownership, based on a $.25 per gallon cost premium for the higher octane fuel.

But a new initiative by **U.S. Department of Energy** national labs, called Optima, aims at developing co-optimized fuels with a range of new engines for light-, medium-, and heavy-vehicle use. Announced by ORNL's Dr. Wagner at this year's SAE High-Efficiency Engines Symposium, Optima is targeting a 30% reduction in petroleum consumption, per vehicle, compared with a projected 2030 base case that uses today's fuels.

Said Dr. Wagner of the two-phase project: "We've put together a team that is looking for low-GHG fuels to work well with redesigned engines, and to be made in billion-gallon quantities." Optima has targeted 2025 for its debut of the new fuels and engines, which it is co-developing with vehicle and engine OEMs and fuel refiners.

Lindsay Brooke

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The hardware set of a typical post-2025 ICE may look something like the 1.8-L gasoline direct-injection compression ignition unit co-developed by Hyundai, Delphi, and the University of Wisconsin's Engine Research team. The four-year, $15-million program completed late last year achieved improved thermal efficiency from advanced low temperature combustion. The combustion regime is "globally stratified but locally stoichiometric"—a melding of Otto and Diesel cycles. The unit runs EGR rates of 25-40% to avoid uncontrolled combustion. (Lindsay Brooke)

FEV's Dean Tomazic noted that in Europe, government-industry alignment has elevated gasoline octane grades overall, with 102 RON the highest, to help optimize recent engine technologies. (Lindsay Brooke)

stated Dr. Wagner. He noted that some multi-cylinder test engines have pushed beyond 55% on the ORNL dyno.

"It will all come down to navigating the combustion space—how best to 'thread the needle' between soot and NOx formation," he concluded.

Toyota's new 8NR-FTS direct-injection turbo engine that recently went on sale in Japan has a claimed peak efficiency of 36%. The 1.2-L unit is both torque-rich (136 lb·ft/185 N·m, generated from 1500 to 4000 rpm) and its claimed fuel efficiency of 19.4 km/L (46 mpg U.S.; 5.15 L/100 km) exceeds the Japanese government's 2015 fuel economy standards by more than 10%.

Also from Japan, **Mazda**'s Skyactiv program is progressing through G1, G2, and G3 development stages toward a marriage of Otto and Diesel cycle characteristics.

"Our target with the G3 is 18:1 compression ratio at lambda 2.5—and up to a 40% improvement in thermal efficiency by setting the ideal pressure and temperature for HCCI combustion," explained Hiroyki Yamashita, Research Manager of Mazda's ICE Technical Center, to the SAE High-Efficiency Engine event audience. He said the G3 program focuses on heat transfer from the combustion chamber and employs a special sprayed-on thermal insulation coating on the piston crown and chamber walls.

And Mazda sets the pace in reducing internal friction across its ICEs, noted Marc Sens, **IAV Automotive**'s Head of Department Thermodynamics/Boost Systems. "We've tested their [G1] Skyactiv engines and their claim of 30% friction reduction over the previous generation is real—very impressive," he said.

VW Group has committed to its own version of the Miller thermodynamic cycle for its new 2.0-L, 140-kW (188-hp) turbocharged, direct fuel injection (TFSI) production engine that will debut in the 2016 **Audi** A4. This unit is another step toward gasoline spark-ignition technology with the fuel consumption [less than 5.0 L/100 km on the NEDC test cycle) and torque capability of the diesel, Dr. Stefan Knirsch, Head of Engine Development, told this year's Vienna audience (see http://articles.sae.org/14140/).

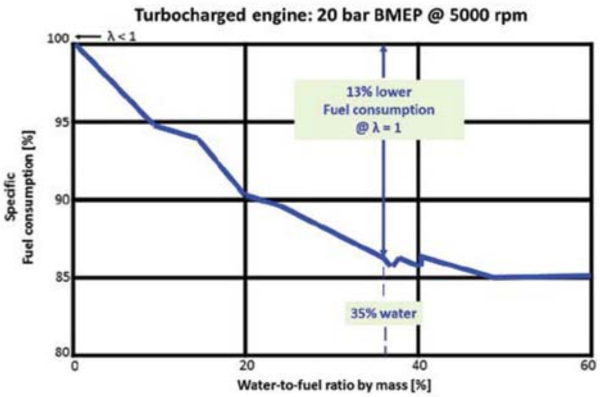
And in pilot development is water injection (WI), a method of improving anti-knock behavior using the charge-cooling effects of water vapor. WI was first proven in World War II air-cooled radial aircraft engines including the mighty **Pratt & Whitney** 18-cylinder R2800 and the 14-cylinder **BMW** 801. At Vienna, Dr. Rolf Bulander, a Robert **Bosch** Board of Management member, announced his company is developing water injection with a customer.

Dr. Bulander noted benefits that have been shown on experimental test engines, including reduction of fuel consumption at high loads and low rpm (up to 4% improvement on the NEDC cycle); reduction or avoidance of fuel enrichment and lower exhaust-gas temperatures at high loads and high rpm; improved "knock" resistance with increased compression ratio; and improved performance.

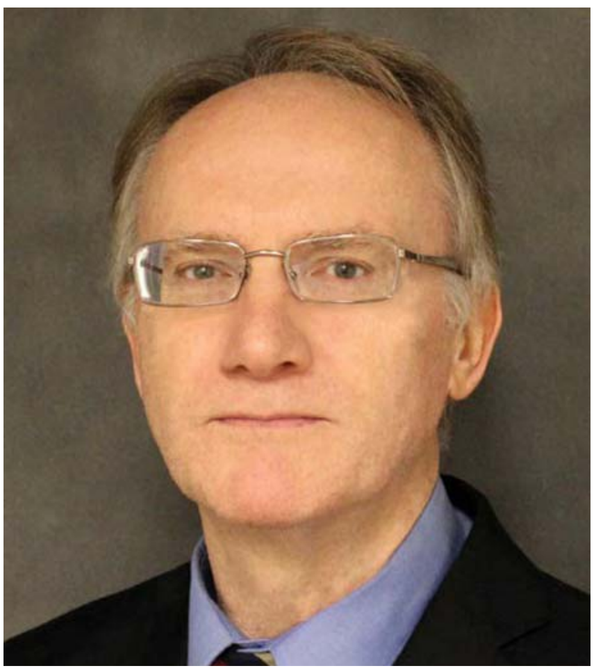
The cooler charge enabled by water injection (part of a fuel-air systems approach) results in lower CO_2 emissions in real driving conditions and the upcoming WLTC test cycle. Injected through the intake port, the WI system includes a water pump, a water rail, and injectors designed to handle the specific challenges of operating with water.

Give me higher octane!

Well over 50% of fuel energy currently is lost through the exhaust and cooling systems, in roughly equal amounts. Waste heat recovery systems will be key to the ICE's survival, experts noted, and are likely to enter the engine-hardware mainstream once costs are mitigated. Significant energy exists downstream of the turbocharger



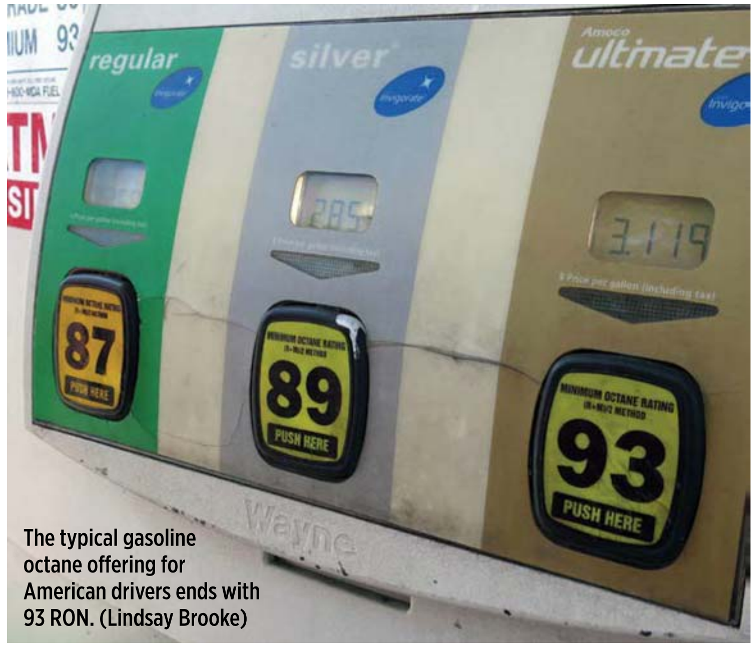
Bosch testing has shown that H_2O injection offers significant potential for reducing fuel consumption and CO_2 emissions in test cycle conditions, as well as for closing the gap between test-cycle and real fuel consumption. On a laboratory engine running at 5000 rpm with BMEP at 20 bar, when the proportion of H_2O in the inlet stream reached 35%, "stoich" operation was enabled. This would eliminate fuel enrichment during full load, at which point fuel consumption can be reduced by 13%.



Connected-vehicle technologies and orders-of-magnitude greater onboard computing power will help drive engine efficiency improvements in the next decade, noted controls expert Chris Atkinson, Sc.D, of ARPA-E.

to power expansion turbines to provide energy storage and/or electrical assist to the powertrain.

"Energy storage, battery, and/or ultracapacitor can capture and utilize otherwise lost heat energy," noted BorgWarner's Grissom. "And independently driven eBoosters (electrically powered assist compressors) can overcome turbo lag, improving higher load efficiency where most fuel is burned." The cost of such systems



The typical gasoline octane offering for American drivers ends with 93 RON. (Lindsay Brooke)

currently is "significant," he admitted.

Turbocharging itself is expected to reach 50% penetration by 2025 for all North American-produced engines, according to UMTRI. At that time, 3- and 4-cylinder engines will comprise over 66% of the passenger car market, while fours and sixes will power over 75% of new light trucks.

High on engineers' list of enablers for next-generation combustion systems is an end to regional/seasonal fuel variations, and higher gasoline octane. "We need to raise the octane floor!" asserted Chris Cowland, Director of NAFTA Advanced Powertrain Engineering at **Fiat Chrysler Automobiles**, during an SAE Congress panel. Known within the industry as a highly vocal proponent of co-optimizing fuel and engine systems, Cowland stated the U.S. needs "a single, high-grade, high-quality fuel like Europe's done."

Moving to a 95-100 RON baseline would yield a 5% fuel-economy gain and would help engineers optimize future designs (see sidebar). Cowland also noted the fuel economy-vs.-CO_2 trade-off related to the carbon level in various fuels diminishing the value of some engine technologies.

"Diesel is attractive in U.S. CAFE, but less so with the CO_2 equation," he said.

Connectivity meets the piston engine

"We can reduce petroleum imports to zero by 2035 by increasing the efficiency of new engines and powertrains by 40%," said Chris Atkinson, Sc.D, Program Director at the U.S. DOE **Advanced Research Projects Agency—Energy** (ARPA-E) and an expert in engine controls and calibration. He is confident that the vehicle connectivity revolution will play an increasing role in improving fuel efficiency and emissions reduction.

"We can do a lot with the 1000 times more real-time computation capability that we will have in the vehicle," Atkinson observed. Real-time, over-the-air adjustments of engine calibration are just the beginning. And autonomous vehicles don't have to be EVs.

"But once we take the driver out of the loop, no more 707-hp [**Chrysler** Hemi] Hellcat V8s will be required—and I have nothing against 707 horsepower," Atkinson teased the SAE audience. ■